# Generating Penetration Path Hypotheses for Decision Support in Multiple Trauma*

Omolola Ogunyemi, M.S.E., Jonathan Kaye, M.S.E., Bonnie Webber, Ph.D.,
Center for Human Modeling and Simulation,
Univ. of Pennsylvania, Philadelphia, PA 19104–6389
John R. Clarke, M.D., FACS
Dept. of Surgery, The Medical College of Pennsylvania, Philadelphia, PA 19129

*We present a 3D graphical system that allows users to visualize different penetration path hypotheses for (multiple) gunshot or stab wounds, using a 3D graphical model of a human body with appropriate anatomical structures. The system also identifies the anatomical structures associated with each hypothesis. The various penetration path hypotheses follow from a combinatorial analysis of the set of surface wounds. The affected structures are determined by performing a detailed interpenetration analysis between 3D models of a penetration path and each anatomical structure within the body.*

## INTRODUCTION

In penetrating trauma, injuries generally follow from organ penetration. To determine the type and magnitude of injuries, physicians use their knowledge of human anatomy in connection with the patient's vital signs and symptoms. In the case of ballistic injuries, the presence of multiple entry and exit wounds often makes this a difficult task, as many different pairings are possible. The goal of this work is to present in a cognitively useful way, the penetration path hypotheses for a set of gunshot wounds, thereby guiding the physician to an initial differential diagnosis.

For any given pair of wounds, we define the *wound path space* as the space of possible trajectories from one wound to the other. A *penetration path hypothesis* may consist of one or more wound path spaces, depending on the number of wounds. This paper addresses the problems of determining and displaying the wound path spaces within the body, calculating all the possible pairings in the case of multiple gunshot wounds, and establishing which anatomical structures are affected for each wound path space. In determining the wound path space for a set of gunshot wounds, it is assumed that penetration paths for bullets follow a continuous line. As the goal of this approach is to present an initial space of likely trajectories rather than consider the entire space of possibilities, ballistic characteristics such as bullet type and velocity, and events such as bullet ricochet are not considered in generating the penetration path hypotheses.

By exploring and displaying all the path and injured organ possibilities for a given set of injuries, the system provides a means for medical professionals to visualize the anatomy involved. This can help to clarify misunderstandings and eliminate from initial consideration those possibilities that would require more complex causal mechanisms to explain.

We provide several ways of visualizing penetration paths and anatomical structures, including external perspectives, as well as through-body navigation. These can serve to enhance the study of anatomy, as Satava[1] has noted:

> these extraordinary perspectives impart a deeper understanding and appreciation of the interrelationship of anatomical structure which cannot be achieved by any other means, including cadaveric dissection.

The organs, skeleton, and skin for the body are displayed using $Jack^{TM}$ and are presented as 3D figures formed from polygonal surface models. These models were developed at Viewpoint DataLabs and come in different resolutions.

To illustrate what the problem of generating all penetration path hypotheses in the face of multiple gunshot wounds entails, we start with the scenario given in the example below.

## EXAMPLE

Consider a patient presenting with four external wounds to the chest: two anterior (left and right) and two posterior (left and right). If we assume that these

*This work has been supported by the National Library of Medicine under contract number NO1-LM-4-3515, and ARPA under grant number DAMD17-94-J-4486. The shapes we are currently using are surface models estimated from Viewpoint DataLabs data. The authors would like to thank Mark-Jason Dominus for his assistance.

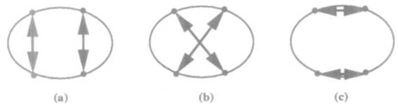

Figure 1: Three hypotheses for two through wounds

correspond to two through wounds *, i.e., the person was shot twice and each bullet entered and exited the body, there are three possible hypotheses (Figure 1): (a) the left anterior wound and the left posterior wound are part of the same wound track, similarly for the right side (the wound tracks are parallel); (b) the left anterior wound and the right posterior wound are part of the same wound track, and the right anterior and left posterior wounds belong to the same wound track (i.e., the wound tracks cross); (c) the left anterior wound and the right anterior wound are part of the same wound track, similarly for the left and right posterior wounds. These three hypotheses yield markedly different potential consequences for a patient. The third would result in mainly superficial injuries whereas in the first case there would be the danger of injury to the lungs, and in the second there would be danger of injury to the lungs, heart and major blood vessels. Figure 1 is just a 2D schematic; the system we describe below exploits full 3D reasoning and visualization.

## PENETRATION PATH ASSESSMENT

There are two steps involved in assessing a penetration path. First, the wound path spaces corresponding to external wounds and possibly internal bullets are computed. Next, an interpenetration analysis is performed between each wound path space and the anatomical structures in the body.

### Wound Path Space Configurations

Currently, gunshot and stab wounds are treated uniformly when analyzing the extent of direct damage and anatomical (structural) alteration that results from them. Wounds are generated in the graphical system by using the mouse to click on a desired location on the surface of a rotatable 3D body model. As suggested by Karpf[2], we identify a wound path space within the body, emanating from the area of contact on the body surface, as the region of space within which the anatomical parts may be affected by the wound.

Gunshot and stab wounds have different wound path spaces corresponding to different regions of uncertainty. For gunshot wounds, the wound path space is represented by two cones joined at their bases. The apices are positioned at the external wounds or at known bullet locations. Thus the greatest uncertainty in any continuous line trajectory corresponds to the area at the adjoining bases of the cones. For stab wounds, the wound path space is represented by a truncated cone, corresponding to uncertainty in the direction of the blade. The wound path space may be adapted to fit a more specific weapon profile.

Stab wounds are straightforward because we need only consider a single wound path space, originating at the external injury. Gunshot wounds, on the other hand, present difficulties because all possible external wound-to-bullet and external wound-to-wound pairings must be determined. In cases of external gunshot injuries, we are faced with different hypotheses about the possible wound path spaces of the projectile(s). The physician will have to determine which, if any of the competing hypotheses is most accurate, based on additional evidence such as test and roentgenographic results. Each hypothesis represents one configuration of pairings for all the known gunshot wounds. In the appendix, we discuss the combinatorics in detail.

### Wound Assessment

Once we have computed the set of possible wound path spaces, we move on to assess the impact of the different hypotheses. For each hypothesis, we use our static, geometric, anatomical model based on $Jack^{TM}$ to determine the anatomical parts that may have been affected based on that configuration of wound path spaces.

The wound path spaces for gunshot wounds are depicted graphically in $Jack^{TM}$ as two conjoined cones. The geometric representations of the wound path spaces and anatomical structures consist of several (in some cases, hundreds) polygonal surfaces which are combined to form a 3D figure. To reduce computation, the anatomical structures that lie in each wound path are found in two steps. The first one involves the use of bounding box intersections and the second, intersections of the polygonal surfaces that make up the geometric representations of the anatomical structures and the wound path spaces. The first step is a quick way of reducing the set of objects that need to be considered in more detail in the second, more computationally intensive step.

In the first step, the smallest axis-aligned parallelepipeds (bounding boxes) that enclose each relevant anatomical structure and each set of conjoined cones (representing the wound path space) within the body is computed. Figure 2 gives bounding boxes for a di-

*Note that other possibilities include the presence of one or more bullets lodged in the body.

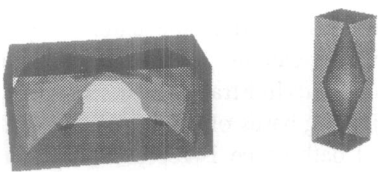

Figure 2: A diaphragm and a wound path space representation and their bounding boxes

aphragm and wound path space cones. The vertices of each bounding box for the wound path cones are then compared with the vertices of the bounding boxes for the anatomical structures of the body. If the vertex of one bounding box lies within the other bounding box, the figures enclosed by these boxes are said to be candidates for intersection. All anatomical structures that are determined to intersect the bullet path cones in this step are stored for the next step. Since bounding boxes give at best a rough estimate of the actual shape and size of a figure, the first step may yield false positives (i.e., detect bounding box intersections in cases where the actual structures enclosed by these boxes are not intersecting). Note for example, that the bounding box for the diaphragm is much larger than the actual figure, due to its concavity, and as a result, bounding box intersection computations involving the diaphragm may yield false positives. The first step will not omit from further consideration any organs that could have been hit on a continuous line path.

In the second step, to find out which anatomical structures lie within a wound path space precisely, we perform another set of checks using the candidates from the first step. In this step, all the faces and edges of the polygonal surfaces that form the geometry of the intersection candidates are examined for intersection with the faces and edges of the wound path cones. For each candidate, the second step determines whether any of its edges intersects with any of the faces of the wound path cones (and vice versa). If so, the anatomical structure is determined to be in the path of the bullet. Since every object in a $Jack^{TM}$ environment has a unique name, the names of those anatomical structures determined to be in a particular bullet path can be displayed.

## 'INTERACTIVE' EXAMPLE

Figure 3 shows one penetration path hypothesis for two through wounds ($Jack^{TM}$ displays are in color - Figure 3 corresponds to a black and white screen dump). Because anterior and posterior wounds are matched left and right, this is similar to case (a) of Figure 1. The body can be rotated, translated and enlarged as desired, and organs can be displayed as shaded objects or in wireframe. Figure 3 shows both a lateral and anterior view of the body, with the wound path spaces, skeleton and abdominal organs displayed as shaded objects, and the lungs, heart, diaphragm, etc., displayed in wireframe.

The text output for the hypothesis in Figure 3 is:

```
Computing intersections for
bullet path #1
    Skeleton parts in path: lcartilage5
    Skeleton parts in path: lcartilage6
    Organs in path: heart
    Organs in path: lungs
    Organs in path: diaph
    Skeleton parts in path: lrib11

Computing intersections for
bullet path #2
    Skeleton parts in path: rcartilage5
    Skeleton parts in path: rcartilage6
    Organs in path: lungs
    Organs in path: diaph
    Organs in path: liver
```

Each anatomical structure referred to in the text output is highlighted in the graphics window at the same time that the text is generated. At the present time, the anatomical structures in a path are listed in anterior to posterior order. In the future, we will list them in order of importance.

## PREVIOUS WORK

Karpf's work on model-based penetration path calculations forms the basis of much of the work presented in this paper. He creates a 3D model of the torso in order to reason about which organs are affected by gunshot wounds, bullet paths, and matching entry and exit wounds.

Wind, Finley and Rich[3] present a method for determining penetration paths as follows. They break the body space up into cubes and assign properties such as tissue density, etc. to each cube depending on the material properties of the anatomical structures in the space surrounded by the cube. Then, following physical laws for energy dissipation, their approach simulates the path of the bullet. From the results of a Monte Carlo simulation, they take the expectation as the likely path.

Eisler et al[4] proposal to enhance procedures for estimating incapacitation from penetrating wounds (bullets, flechettes and bomb fragments) and improve existing analysis of wound tracts and penetration depth. They calculate penetration path depths using retardation algorithms.

Fackler, Bellamy, and Malinowski[5] discuss missile-tissue interaction, and give examples of cavitation caused by different shells. They identify the primary issues to be considered for potential tissue disruption

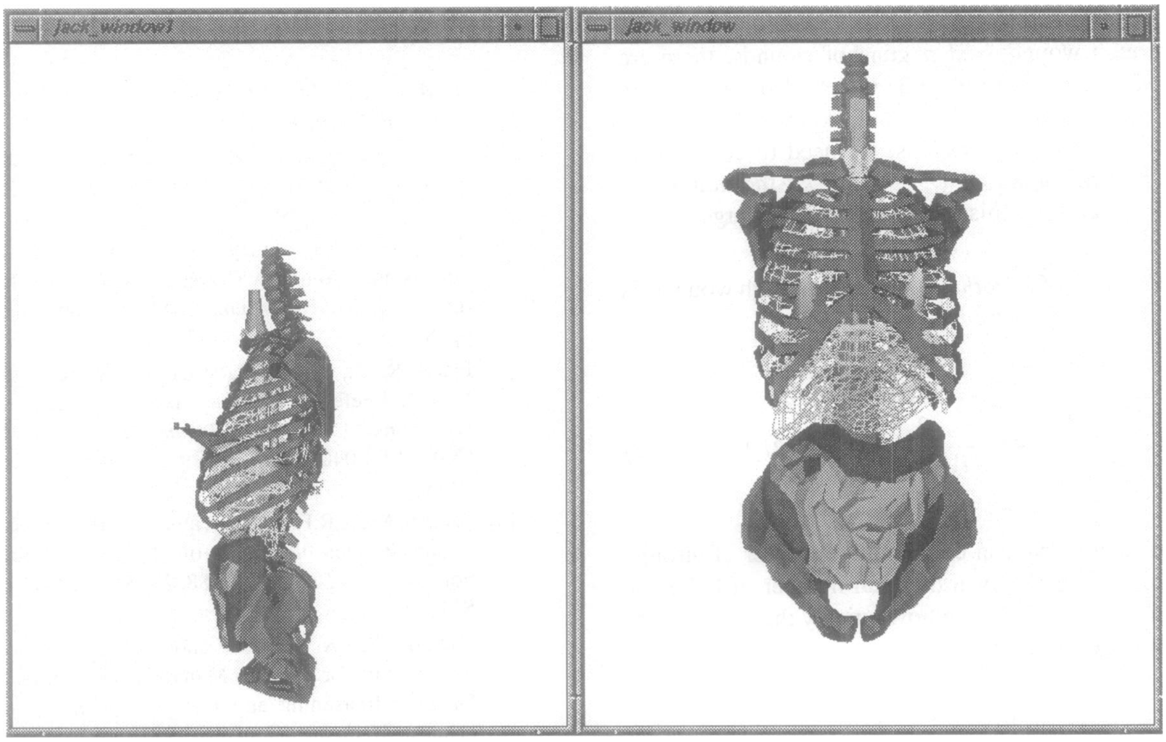


Figure 3: Lateral and anterior views of a penetration path hypothesis with two through wounds

as: (1) the penetration depth of the projectile; (2) the size of hole it makes; and (3) any unusual deviations in the direction of the projectile's course through tissue.

## CONCLUSION

Anatomical knowledge is critical for emergency physicians and their students to assess possible organ involvement based on penetration paths. This project seeks to assist them, with a 3D anatomical model that the user may freely orient, in visualizing which organs may have been injured as a result of gunshot and stab wounds. In generating possible hypotheses for gunshot wounds, we have introduced the idea of considering the *wound path space*, or the *space* of possible trajectories given a starting and ending point, as opposed to trying to identify or recreate the specific trajectory.

The system presented has potential emergency room applicability. Attending physicians can obtain the system's penetration path analysis and a list of the anatomical structures affected at the same time that roentgenographic information is made available to them.

Another application for the system is in assisting diagnostic programs like TraumAID[6] in improving their geometric and anatomical reasoning.

We have discussed our preliminary results and methods. We are developing this tool as an aid to physicians and students—as a concrete visual image upon which to focus subsequent diagnosis.

## APPENDIX: COMBINATORICS

This section discusses the number of different injury hypotheses, given one or more gunshot wounds.

With one external wound, there is only one possibilty: a path between the external wound and a bullet retained within the body. With two gunshot wounds, there is only one *pairing*, that is a match between two external wounds (a through wound) and two possible matches between an entry wound to known bullet (we call a 'single-entry wound'). The number of *hypotheses*—each a set of pairings where each external gunshot wound appears in exactly one pairing and each known bullet (if any) appears in exactly one pairing—is thus small.

If we know that there are $i$ through wounds, then the number of ways of choosing a set of external wound pairings is

$$\frac{\prod_{m=0}^{i-1} \binom{n-2m}{2}}{i!} \qquad (1)$$

(we assume that $\prod_{m=0}^{i-1} f(x) = 1$ when $i < 1$). With $i$ through wounds and $n$ gunshot wounds, there are $n - 2i$ single-entry wounds which also means there are $n - 2i$ bullets. If we don't know which bullets match which entry wounds, we need to consider all possible permutations $(n - 2i)!$. As the number of bullets increases, this term becomes very large.

The number of *hypotheses*, given $i$ through wounds, is

$$\frac{\prod_{m=0}^{i-1} \binom{n-2m}{2}}{i!}(n-2i)! \qquad (2)$$

Equivalently, we can compute the number of through wounds if we're given the total number of bullets $b$, namely $i = \frac{n-b}{2}$. To see how quickly this grows, consider some values:

| $n$ | $b=0$ | $b=1$ | $b=2$ | $b=3$ | $b=4$ | $b=5$ |
|---|---|---|---|---|---|---|
| 3 | | 3 | | 6 | | |
| 4 | 3 | | 12 | | 24 | |
| 5 | | 15 | | 60 | | 120 |

(3)

If we don't know how many through wounds or total bullets there are, we could sum the results from $i = 0$ to $i = \lfloor n/2 \rfloor$ to compute this value, where $n$ is the number of gunshot wounds:

$$\sum_{i=0}^{\lfloor n/2 \rfloor} \frac{\prod_{m=0}^{i-1} \binom{n-2m}{2}}{i!}(n-2i)! \qquad (4)$$

This results in

| $n=2$ | $n=3$ | $n=4$ | $n=5$ | $n=6$ |
|---|---|---|---|---|
| 3 | 9 | 39 | 195 | 1185 |

(5)

Left unconstrained, there are obviously a great number of possible hypotheses. For that reason, we need to develop methods to assist in filtering highly-implausible pairings.

Reference


[1] R. M. Satava, Virtual Reality surgical simulation: the first steps. *Surgical Endoscopy*, 1993. 7: pp. 203 - 205.

[2] L. J. Karpf, Model-based penetration path calculations for the diagnosis of multiple trauma. Master's Thesis, University of Pennsylvania, 1990.

[3] Wind, G., R.W. Finley, and N. M. Rich, Three-dimensional Computer Graphic Modeling of Ballistic Injuries. *Journal of Trauma*, 1988. 28 (Supplement 1): pp. S16-20.

[4] Eisler, R. D., A. K. Chatterjee, G. H. Burghart, and J. A. O'Keefe IV, *Casualty Assessment of Penetrating Wounds from Ballistic Trauma.* Tech Report MRC-COM-R-93-0402(R1), Mission Research Corporation: 1993.

[5] Fackler, M.L., R.F. Bellamy, and J. A. Malinowski, The Wound Profile: Illustration of Missile-Tissue Interaction. *Journal of Trauma*, 1988. 28 (Supplement 1): pp. S21-29.

[6] Webber, B., R. Rymon, and J. R. Clarke, Flexible Support for Trauma Management through Goal-Directed Reasoning and Planning. *Artificial Intelligence in Medicine* 4(2), April 1992, pp. 145-163.